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Quantifying the physical alterations of river reaches using a regional river morphology reference model. A step towards river restoration.

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ABSTRACT: The aim of this study is to quantify the physical alterations of alluvial rivers and reach a better understanding of the links between these alterations and the ecological quality (derived from the European Fish Index, EFI) of river channels. This is an essential step towards river restorations, which are increasingly being considered in order to meet "good ecological status" as defined by the European Water Framework Directive. The methodology of this study involves comparing physically altered river reaches (mainly reshaped rivers) to a reference model built from data collected on 28 non-altered sites in the chalky parts of the Seine Basin (northern France). The physical quality of the reaches is determined from eight morphological variables such as the bankfull discharge, the channel width, the width/depth ratio and the depth of pools present. These variables are estimated at the reach scale (i.e. about 20 times the channel width) from topographical surveys and discharge measurements. The hydrological regime (at mean and bankfull flow) and river substrate (sediment composition, size and transport rate) are also considered as morphological drivers. Our study shows that a reference model for natural river reaches may be built from their morphological characteristics in regions with homogenous geology and hydrology. Physically altered reaches have statistically different characteristics from the reference model. From biological data (relative to fish populations) the structure of the fish communities in natural and altered reaches was characterised and fish index was calculated, showing a link between physical alteration and ecological quality.

Keywords: Channel morphology, River restoration, Bankfull discharge, Biological alteration

1 INTRODUCTION

The European Water Framework Directive (WFD) aims to achieve "good ecological status" of European rivers by 2015. In order to meet the WFD objectives, a certain amount of river reaches will have to be restored. A better understanding of the links between physical alterations of river channels and their ecological quality is necessary in order to optimise river restoration. Although, clear links between the physical and the biological environments have been demonstrated, the consequences of physical alterations of river channels on their biocenoses are less clear. Physical alterations do not necessarily lead to ecological alterations. The responses of aquatic communities to anthropogenic alterations such as partial embankment, channel reshaping or increases in sediment size are not clear. These responses are not uniform and depend on many parameters including the type of river and the magnitude of the perturbation. A better understanding of the links between physical alterations and ecological quality is a precondition to planning river restoration that aim to attain good ecological status.

The aim of this project is to better understand these links by studying several tributaries of the Seine River in northern France using a three-step process. The first step consists of determining the morphological characteristics of about 30 natural (non-altered) river reaches through the analysis of response variables such as the channel geometry, the bankfull discharge and the sediment size. Regional models are constructed based on this data (i.e. the reference model). In the second step, altered river reaches are compared to the reference situation previously defined and divergences from the reference model are measured. The final step seeks to determine the ways in which physical alterations of the river channel may contribute to modifications in the biological communities present.

2 STUDY AREA

All of the studied catchments are located in a region that is relatively homogenous in terms of geology, geomorphology and hydrology (Figure 1). All of the rivers flow on Upper Cretaceous sediment (chalky) in the Paris Basin, in northern France. 28 sites were selected in reaches as natural as possible in order to build the physical reference model. Reaches were considered as natural when their hydrology had not been modified (at least at high flow), when sinuosity was pronounced and when there were no embankments and no weirs. Another 11 sites were selected on reaches where there was a clear anthropogenic influence (mainly channelization, reshaping and embankments). These sites were selected because of the very low sinuosity of their courses, which indicates that river channel has been modified by men.

The 39 basin areas of the reaches studied range between 9 and 1029 km² (53 and 350 km² for the altered reaches); their slopes are gentle and range between 0.02 and 1 % (mean 0.3%); the median sediment size ranges between 1 and 60 mm. About half of the reaches are gravel bed rivers, while the others are sand bed rivers. All gravel bed reaches are located in the western part of the basin (Normandy) where they flow on chalk with flint pebbles. Slopes are also generally steeper in this part of the Seine Basin.

Rivers that flow on chalky substratum have specific morphological, hydrological and hydrogeological characteristics which control their ecological behaviour and the organisation of their biocenoses (Berrie, 1992; Wood et al., 2001). Their hydrological regimes are dominated by groundwater flow. Sear et al. (1999) showed that the Base Flow Index (BFI) (Tallaksen & Van Lanen, 2004), which indicates the contribution of groundwater to the river discharge, ranges between 0.53 and 0.99 in several chalky British rivers. In this study, 75% of the rivers studied have a BFI higher than 0.85. The preponderance of groundwater means that seasonal and inter-annual flow does not fluctuate greatly and that environmental conditions are relatively stable. In natural conditions, the stability of the hydrological regime also seems to influence the cross-section morphology of the channel (Sear et al., 1999). Whiting & Stamm (1995) showed some typical features of groundwater dominated rivers: a high width/depth ratio, a lack of alluvial bars, a low rate of sediment transport, low shear stress values and a bankfull discharge frequently attained, leading to ground saturation of the floodplain.

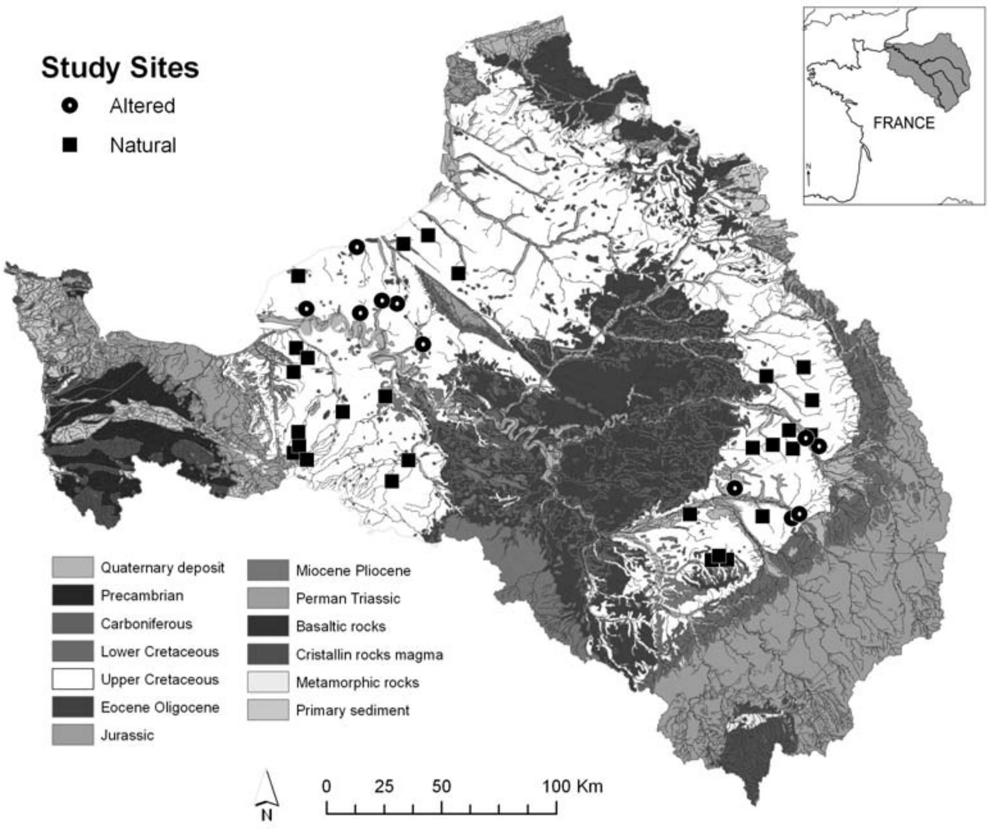

Figure 1. Study area. Geological map of the Seine Basin and location of the study sites.

3 METHODOLOGY

The methodology of this study involves comparing the ecological status of physically altered rivers with a reference model built from about 30 non-altered sites. In order to integrate the upstream and downstream impacts of the anthropogenic perturbations, this multi-site study is based on eight morphometric parameters which allowed the physical condition of not-altered rivers to be defined: the bankfull discharge (Q_b), the bankfull width and depth (W and d), the width/depth ratio (W/d), the sediment size (median diameter on riffles, D_{50}), the pool depth (d_p) and the coefficients of variation of the depth and the Froude number calculated for each cross-section at low flow (CV_d and CV_Froude).

Most of morphological variables used to study the physical quality were measured at the bankfull stage. In natural conditions bankfull discharge usually results from the river's auto-adjustments to the basin characteristics. Different authors have constructed regional models linking channel characteristics to the bankfull discharge (Petit & Pauquet, 1997).

In the first step of this study, linear regression models (reference models) were constructed using the eight variables presented above as a function of three independent variables:

- (1) the catchment size (BA);

- (2) the ratio between the 2-year return period peakflow and the mean annual discharge (QIXA2/QA) which reveals the magnitude of flood events. In groundwater dominated rivers peakflows are strongly reduced (Sear et al., 1999). This ratio therefore indicates the contribution of groundwater flows to the general hydrological regime.

- (3) a regional variable (REG) allowing eastern and western rivers to be separated. Rivers to the east (Champagne region) flow on chalky ground where flint is not present and rivers to the west (Normandy) are generally gravel bed rivers due to the flint pebbles present in the chalk.

In the second step of our study, the modifications to the physical characteristics of altered rivers were measured by comparing their morphometric parameters with the reference conditions previously defined. The models allow the value of the eight variables in natural conditions to be estimated, taking into account the global environmental conditions described by the three independent variables: BA, QIXA2/QA and REG. The residuals between the values observed and the values calculated using the models were computed and used to determine which variables best highlight the morphological changes caused by alterations such as channelization, reshaping and embankments.

Reaches measuring 15 to 20 times the bankfull width were studied in order to include at least two riffle/pool sequences. The bed morphology was determined from a topographical survey of 15 to 20 cross-sections at intervals equal to the bankfull width. The water level was measured twice, at low and high discharge (when possible) allowing the bankfull discharge to be calculated by extrapolation. The definition of the bankfull stage has been discussed by many authors in the literature (Leopold et al., 1964; Andrews, 1980; Harrelson et al., 1994; Castro & Jackson, 2001; Navratil et al., 2004). In this study, the bankfull stage was located on the bank based on one of the methods suggested by Navratil et al. (2006) in their comparative study of bankfull stage definitions (i.e. the bankfull stage corresponds to the inflection point on the top of the bank just before the bank becomes flat). It was then possible to determine the morphological features of the channel at the bankfull stage.

In 20 reaches out of 39, high flow was not observed during the time the study was conducted. Bankfull discharges had therefore to be modelled using *Fluvia*, a one-dimensional, open-channel, steady and step backwater model (Baume & Poirson, 1984). In order to compare the discharges calculated using the model with the discharges calculated in the field, Fluvia was also applied to 10 reaches where high and low flow had been surveyed. For these 10 reaches, bankfull discharges calculated from the model were similar to the bankfull discharges extrapolated from two discharges measured (maximum difference of 10%).

Hydrological data were provided by the French Regional Department of the Environment from 49 gauging stations present in the area. Unfortunately every river studied was not equipped with a station and extrapolations had to be made. The mean annual discharge and the 2-year return period peakflow were then estimated based to the QIXA2 value observed at the closest gauging station (within the same geology) using the ratio of catchment areas.

The D_{50} was measured on riffles using Wolman's (1954) technique in the gravel bed reaches and by sieving in the sandy reaches. The depth of the pools was calculated using the methods proposed by Carling & Orr (2000) based on the longitudinal profile of the bottom of the bed.

By taking into account the needs of species in terms of habitat, it was also possible to compare the characteristics of the biological communities of the altered and non-altered rivers. Data on fish communities were collected allowing the structure of the aquatic communities in the reference conditions to be identified. At this stage, they concern only fish populations and are available for 10 of the natural sites and 10 of the altered sites. They come from electric fishing and were collected using the following methodology:

- In rivers narrower than 8 to 10 m, the entire reach was prospected. The amount of anodes was adapted to the channel size (1 anode for each 4 to 5 m of width).
- In larger rivers, the prospection was not complete. The sampling scheme consisted of distributing tens of sampling units (about 10 m² each) throughout the reach in order to cover the entire habitat diversity.

The fish sampled were then identified and measured individually. The European Fish Index (EFI) was used to asses the alterations to the fish communities on each site.

4 RESULTS AND DISCUSSION

4.1 *Regional reference models*

In the first step of the analysis, statistical relationships were made for the natural sites. They are based on linear regression models linking the channel morphology and sediment size to one or two of the three independent variables selected: BA, QIXA2/QA and REG. Every one of the eight morphological variables is significantly linked to at least one of the three independent variables (Table 1 and Figure 2).

As predicted, the bankfull discharge is well correlated and increases with the basin area. The model also shows that rivers with attenuated peakflows (i.e. low QIXA2/QA) have on average lower bankfull discharges. The bankfull width also increases with the catchment size. However, the REG parameter shows that, for equivalent catchment sizes, the rivers of the western part of the Seine Basin are larger. Mean depth increases with the basin area and the W/d ratio varies according to the location. The highest value may be found in the reaches of Normandy where sediments are coarser, which is coherent with the literature (Knighton, 1998). Logically, Figure 2 shows that pools tend to be deeper in the larger rivers. This trend is however rather weak (r^2=0.155) and a large variability within reaches is observed.

The last two parameters which indicate the diversity of the habitats, CV_d and CV_Froude, are not linked to the river size but increase in line with the QIXA2/QA ratio The reaches characterised by attenuated peakflows therefore have a range of depths and flow conditions that are more homogenous than rivers with well marked flood events. These characteristics correspond with the traditional features found in the chalky rivers (Sear et al., 1999).

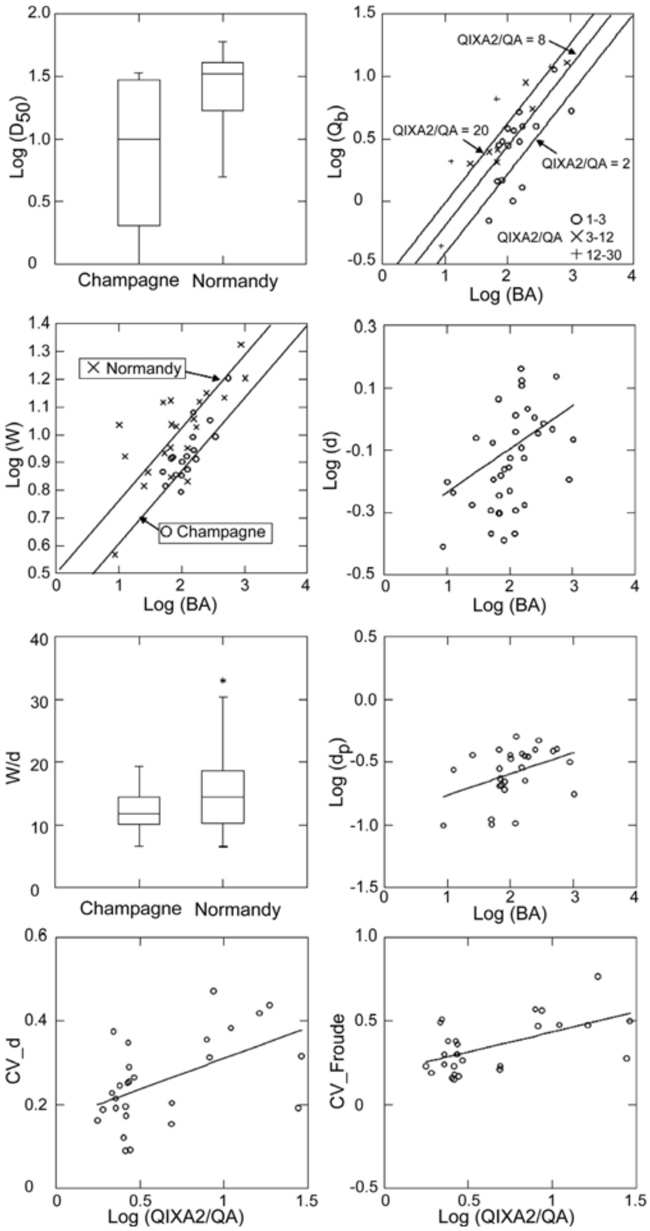

Figure 2. Evolution of the eight morphological variables with the three independent variables that describe the global environmental conditions.

4.2 *Divergences between altered reaches and the reference model*

The differences between observed values and the values predicted using the reference models (i.e. residuals) for natural and altered sites were computed for each of the eight morphological variables (Figure 3).

Table 1. Linear models between each of the 8 morphological variables and the three independent variables. Only variables with significant effect (p<0.05) are include in the final models.

		r^2	Intercept value	BA		REG		QIXA2/QA	
				Coeff	p	Coeff	p	Coeff	p
D_{50}	Particle median diameter	0.268	0.887			0.540	0.006		
Q_b	Bankfull discharge	0.640	-1.155	0.685	0.000			0.369	0.013
W	Mean width	0.737	0.405	0.260	0.000	0.111	0.002		
d	Mean depth	0.317	-0.543	0.186	0.002				
W/d	Width/depth ratio	0.165	12.774			5.145	0.036		
d_p	Mean depth of pools	0.155	-0.934	0.170	0.042				
CV_d	CV* of depth	0.274	0.163					0.147	0.005
CV_Froude	CV* of Froude number	0.319	0.195					0.239	0.002

* Coefficient of variation (i.e. the ratio of standard deviation to the mean)

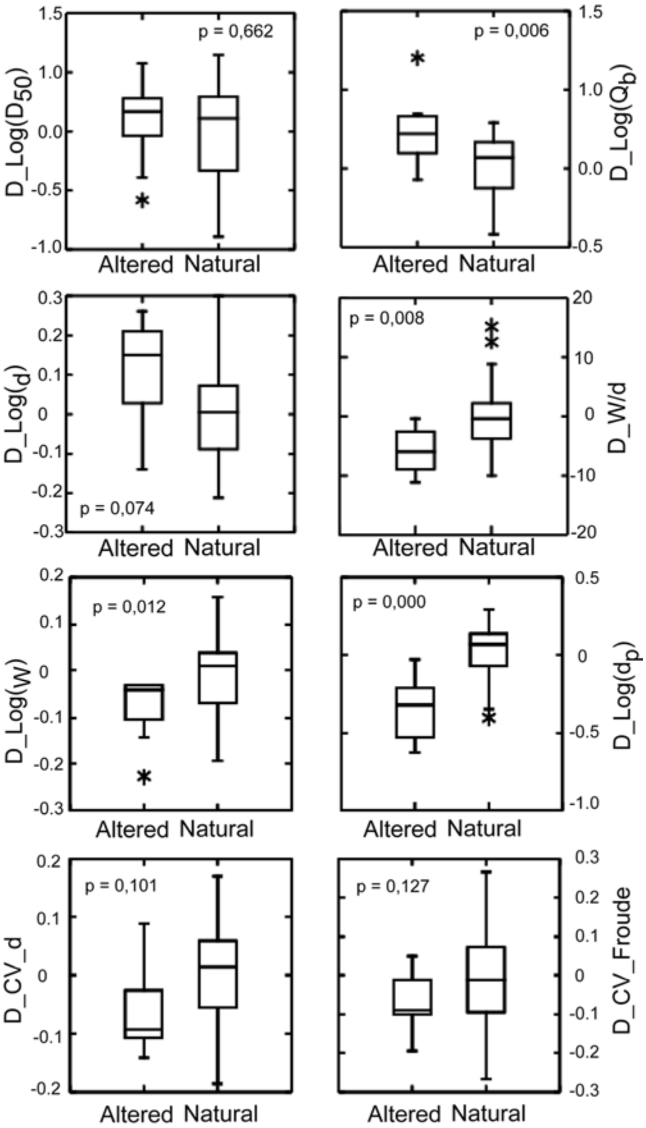

Figure 3. Differences between observed values and values predicted by the reference model for the 8 morphological variables in natural or altered reaches. The P values are the probability values associated with the ANOVA test.

In a certain number of cases, some residual values show statistically significant differences between natural and altered reaches. Natural reaches have in general a lower bankfull discharge, a larger width, a higher W/d ratio and deeper pools. Natural rivers also seem to be shallower but have a greater variability of depth and flow conditions. However, these last three observations were not significantly demonstrated ($p > 0.05$). Meanwhile, no differences were observed concerning the sediment size.

For the four significantly different variables ($p < 0.05$) in altered and natural reaches, the ranges of values overlap. It is therefore not possible to classify natural and altered reaches using only one unique variable. A discriminant analysis of residual values was then undertaken. It revealed that altered reaches may be distinguished from natural ones based on the following three residuals calculated from the difference between the observations and the models: D_Log(dp), D_Log(Qb) and D-Log(W) (i.e. the depth of the pools, the bankfull discharge and the mean width).

The analysis defines a factorial axis which corresponds to a linear combination of these three variables (Figure 4). On this axis the natural reaches tend to have negative coordinates while altered reaches have positive ones. Factorial coordinates of the altered reaches are greater as their morphological characteristics are different from those found in natural conditions. Of the 40 reaches studied, the discriminant analysis allows every altered reach to be distinguished from the natural ones.

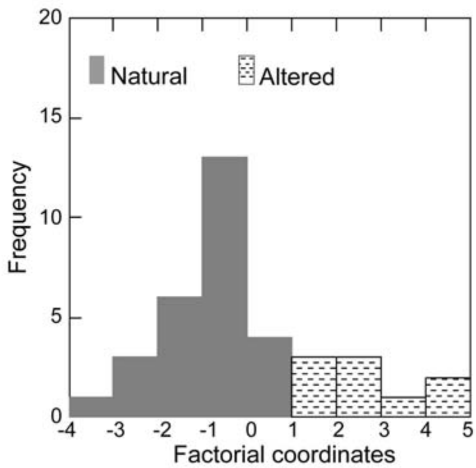

Figure 4. Distribution of the values of the coordinates defined by the factorial analysis.

4.3 *Impacts on biocenoses*

The fish population data was analysed using a biological indicator based on fish populations, the European Fish Index (EFI). The EFI is a multi-parameter index which is based on 10 variables that describe different aspects of the fish population structure and composition. EFI values potentially range between 0 and 1 (1 corresponding to the reference situation).

Figure 5 shows that in general, the altered reaches tend to have lower EFI values than in natural reaches. This confirms the negative impact of physical alterations of rivers, which induce modifications to the fish population. It also confirms that classical bio-indicators may be used to detect physical alterations. The difference between natural and altered rivers, illustrated in Figure 5 may not be statistically tested because of the small number of observations.

However, the observed trend is not systematic. Half of the altered sites yield index values similar to those observed in natural reaches. In some cases, physical alterations to the channel have no consequences on fish populations (at least when considering the variables used in the index).

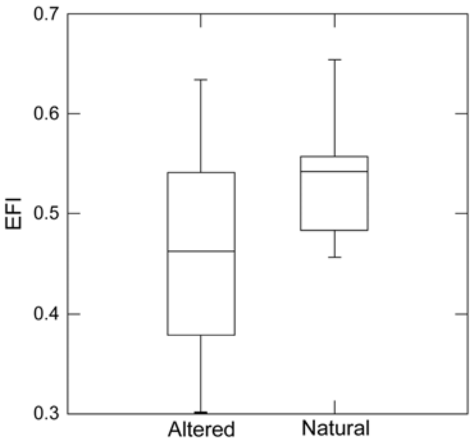

Figure 5. EFI values for altered and natural sites (1 corresponds to the reference situation).

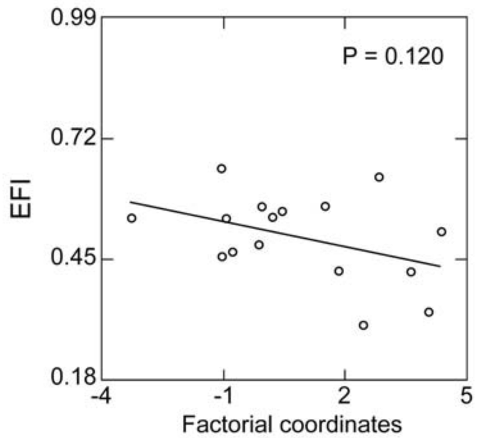

Figure 6. Evolution of EFI values with the factorial coordinates defined by the discriminant analysis.

EFI values were related to the factorial coordinates (Figure 6) of the reaches from the discriminant analysis of the morphological variables presented above (used as an indicator of morphological alteration of rivers). The general trend shows that EFI values decrease as the factorial coordinates of the discriminant analysis increase. This indicates that the more the morphological characteristics of the altered reaches differ from the natural ones, the higher the degradation of the ecological condition of the fish populations is. However, this trend is limited and is not statistically significant ($P = 0.12$). In some cases, the lowest EFI values do not represent the strongest morphological alterations.

At this stage, the results relating to fish populations should be treated with caution and may not be generalised because (i) of the relatively small amount of reaches included in the analysis, (ii) this study concerns a particular type of river dominated by groundwater flow, and (iii) only one type of alteration (channelization, reshaping) has been considered. However, these results correspond with the results of other studies which indicate that fish bio-indicators (and in particular EFI) respond better to water quality alterations than to physical degradation of the channel (Schmutz et al. 2007).

5 CONCLUSION

In order to evaluate the rate of physical alteration of river reaches the results presented in this paper are rather encouraging. Though they may not yet lead to an index of physical alteration, they show that when several morphological parameters are considered, it is possible to use a reference situation to which possibly altered reaches may be compared. This is very interesting when evaluating restoration needs and planning restoration schemes. In the chalky part of the Seine Basin, three parameters are predominant: the depth of pools, the bankfull discharge and the width. They allow clearly channelized and reshaped sites to be distinguished from natural ones.

This clearly shows the consequences of anthropogenic pressure on river morphology. The impacts on river's ecological status have also been highlighted but are still less clear. The small amount of data, the parameters used, the particularity of the region studied and the complexity of the processes may probably explain the weakness of the results.

In order to improve the physical and ecological results, the size of the sample of altered reaches has to be increased. In addition, by increasing the variety of alterations considered, by using macroinvertebrates indexes, and by studying regions with other hydrologic and geologic proprieties, it should be possible to improve the quality of the statistical adjustments and better understand the link between alterations and ecological responses to them.

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